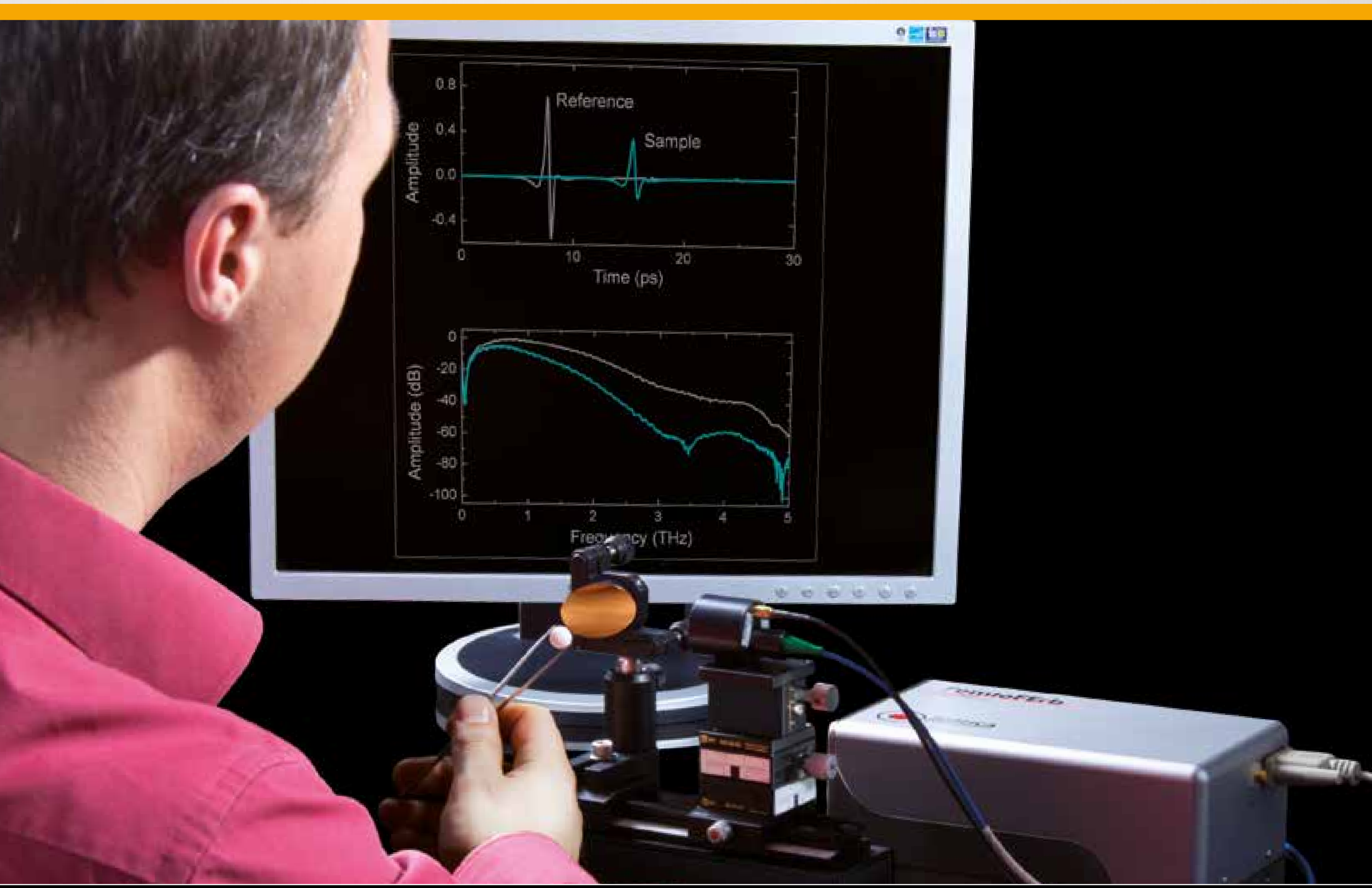
Terahertz Technologies

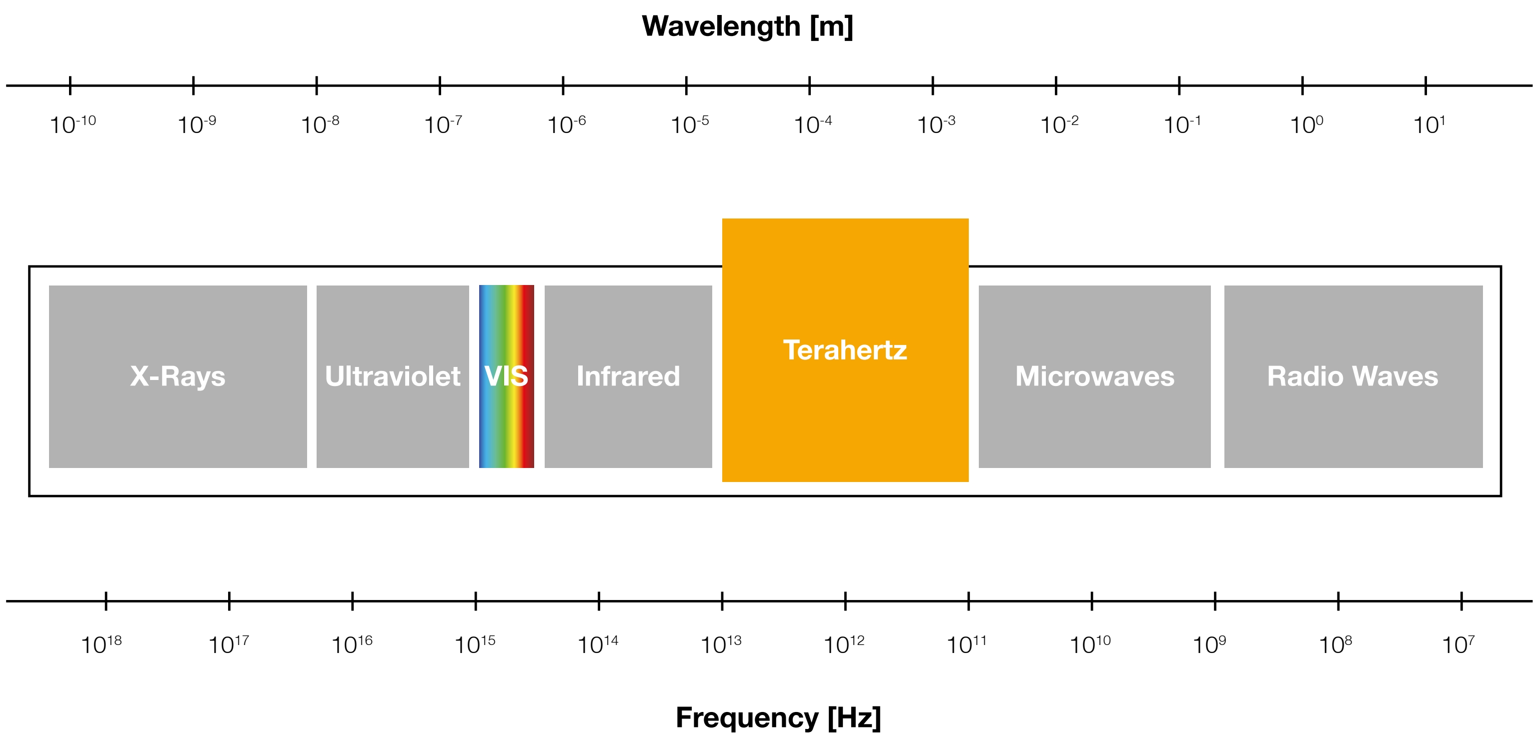
Lasers, Accessories and Solutions



Plastic Inspection
Paint and Coating Layers
Paper Quality Control
Hydration Monitoring
Ultrafast Dynamics
Gas Sensing

TOPTICA PHOTONICS
A Passion for Precision

Contents



Terahertz Waves
The Final Frontier of the Electromagnetic Spectrum

Between microwaves & infrared

The terahertz range refers to electromagnetic waves with frequencies between 100 GHz and 10 THz, or wavelengths between 3 mm and 30 µm. Light between microwaves and infrared has some unique properties. Terahertz waves can "look inside" plastics and textiles, paper and cardboard. Many biomolecules, proteins, explosives and narcotics also feature characteristic absorption lines – so-called spectral "fingerprints" – at terahertz frequencies. Unlike X-rays, terahertz waves do not have any ionizing effect and are generally considered biologically innocuous.

Closing the terahertz gap

For a long time, it has been difficult to generate intensive, directional terahertz radiation, and the terahertz range was considered the final frontier of the electromagnetic spectrum. Now, frequencies between 0.5 and 10 THz have become the domain of laser-based techniques. Optoelectronic approaches use either femtosecond lasers or tunable diode lasers. Photomixers, photoconductive switches or nonlinear crystals convert the near-infrared laser light into terahertz waves, either broadband or spectrally resolved. The terahertz gap is bridged at last.

The complete portfolio

TOPTICA has been working with leading researchers in the terahertz arena from day one and is now able to serve scientists and engineers working with the two most important optoelectronic approaches – pulsed and continuous-wave (cw) terahertz generation. Our ultrafast FemtoFiber lasers form the basis of the **TeraFlash** system, a complete time-domain spectroscopy platform with excellent bandwidth and dynamic range. On the other hand, our precisely tunable DFB diode lasers are the perfect match for GaAs or InGaAs photomixers, as used in our **TeraScan** frequency-domain systems.

Applications

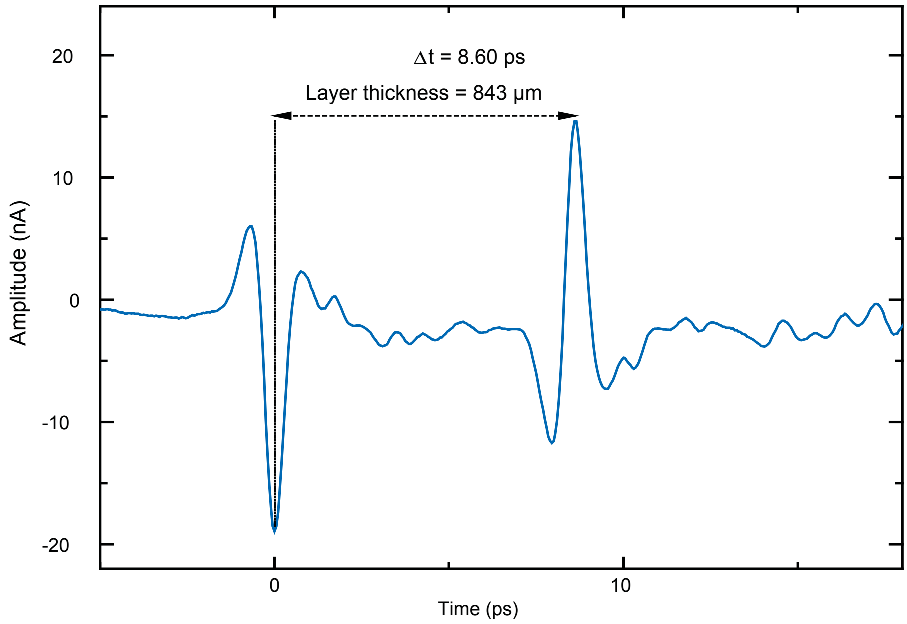
› Plastic Inspection
› Paint and Coating Layers
› Paper Quality Control
› Hydration Monitoring
› Ultrafast Dynamics
› Gas Sensing
› Fundamental Physics

Terahertz Applications

Plastic Inspection

Many polymeric materials exhibit a pronounced low absorption of terahertz radiation, a property successfully used for contact-free analysis and non-destructive testing. Pulsed terahertz radiation provides information of an object's thickness, even in multi-layered samples, via time-of-flight techniques: Each layer interface reflects a part of the incident pulse, and the time elapsed between the arrivals of pulse "echoes" from either side is directly proportional to the optical thickness of that layer.

Applications of terahertz radiation for plastic inspection are not limited to just thickness profilometry. Scanning a sample, with the help of a terahertz beam, turns a one-dimensional profile into a three-dimensional image that pinpoints subsurface cracks, voids and delaminations. Spectroscopic techniques determine the absorption coefficient and refractive index of compound materials. The potential of terahertz technologies for quality and process control in the plastic industry seems almost unlimited.



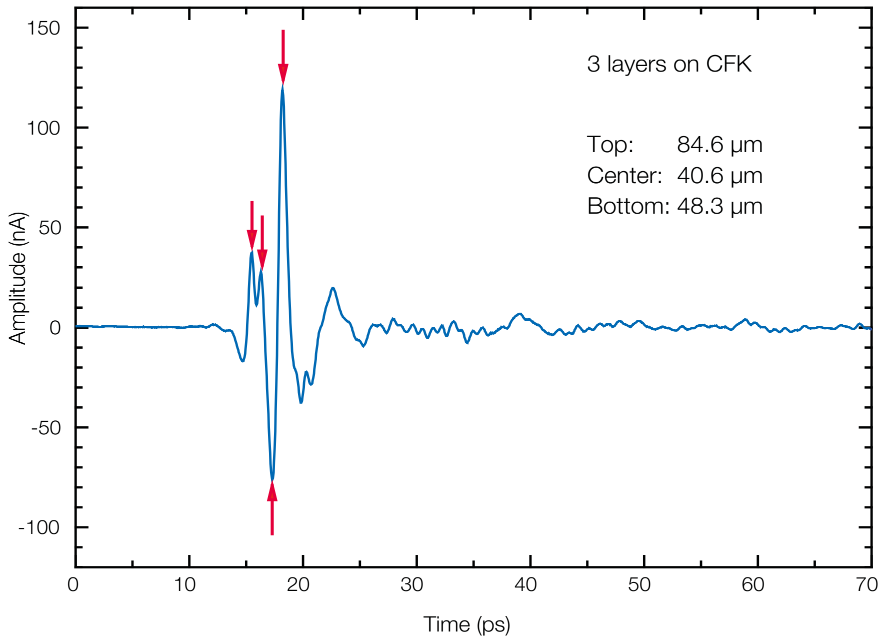
Pulse trace obtained with TOPTICA's TeraFlash and a bottle made of high-density polyethylene. The pulse spacing of 8.60 ps corresponds to a wall thickness of 843 µm.

Paint and Coating Layers

Measuring the thickness of paint layers forms an important quality-control step in automotive manufacturing. The layers not only lend a vehicle its color, but also provide protection against scratches, corrosion and chemicals. To this end, color pigments, smoothing "primers" and protective coatings all cover a substrate made of steel or carbon-fiber composites, with each layer having a thickness of a few ten microns only.

Most of the traditional thickness gauges require physical contact to the layer under test, and fail in case of non-metallic substrates. Terahertz pulses, by contrast, resolve the thickness of each individual layer, as long as adjacent coatings differ in their refractive index.

Layer thickness analysis combines time-of-flight measurements of terahertz pulse echoes with elaborate data post-processing, which involves Fourier transformations and advanced fitting routines. This method has proven successful: TOPTICA's customers have achieved thickness measurements down to 20 µm, with accuracies on the single-micron level.

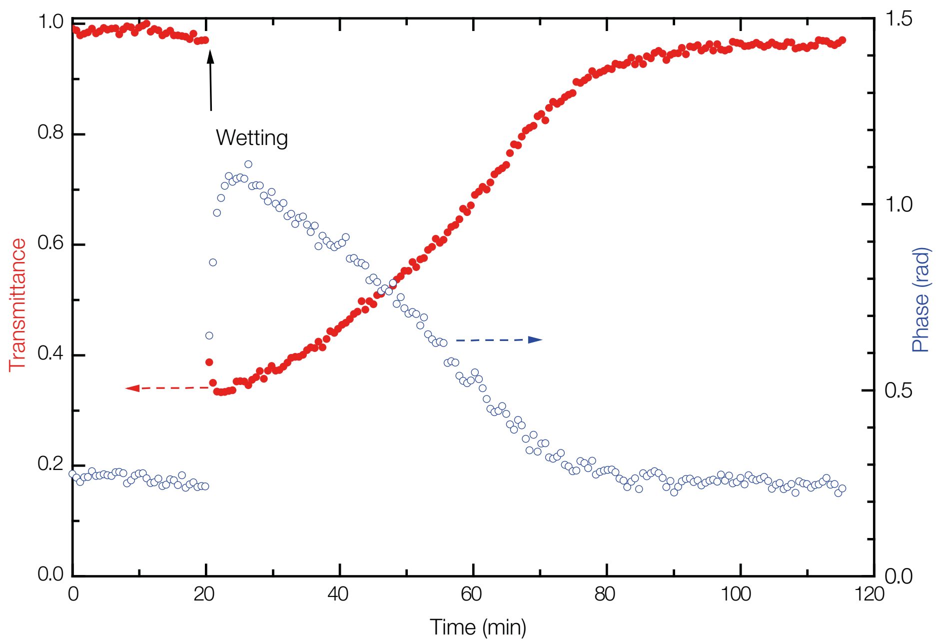


Pulse echoes of a carbon-fiber composite substrate with three different coating layers. The arrows indicate the reflections at the respective interfaces.

Paper Quality Control

Water vapor strongly attenuates terahertz waves, and the liquid state of water has an even stronger effect. On the other hand, water also provides a stark contrast in reflection-mode terahertz imaging. Measuring a sample's transmission or reflection properties yields quantitative information on its water content. A new application emerging in the field of industrial process control assesses paper humidity in paper production lines. Here, terahertz-based measurements provide the long-sought-after alternative to radioactive emitters recently used.

The humidity content is not the only property of paper that terahertz light can probe. Terahertz waves provide information about the thickness and mass density of paper sheets. Terahertz-based imaging systems can "look" inside envelopes or cardboard boxes, and can, for example, check whether or not a box of pharmaceuticals encloses the required package inserts – a further step towards 100% screening in quality control. The combination of powerful terahertz emitters and fast Schottky detectors achieves imaging speeds unmatched to-date.

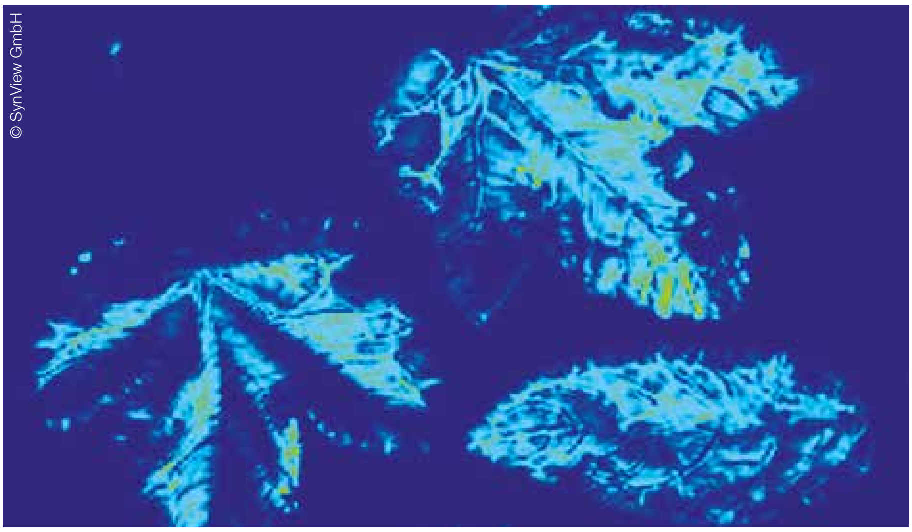


Drying process of tissue paper, monitored with cw-terahertz radiation at 200 GHz. Both amplitude and phase of the terahertz beam vary with the humidity level of the sample.

Hydration Monitoring

The high sensitivity of “water-contrast” terahertz imaging allows in-situ measurements of the water content of plant leaves. This helps to avoid drought stress and to optimize irrigation strategies, a topic of relevance for agricultural crops grown in arid regions, where both desertification and water shortages present serious threats. Terahertz imaging visualizes not only the leaf veins, but can identify regions of low water content as well. Studies of water transport mechanisms in plants, or “plant physiology” in general, could be prospective applications for terahertz-based imaging and monitoring systems.

Whilst many research groups world-wide have confirmed the general suitability of both frequency-domain and time-domain systems for terahertz imaging, continuous-wave systems in particular have become intriguingly compact and inexpensive. In addition, they enable users to choose the operating frequency in dependence of the required spatial resolution, and the transmission properties of the sample under scrutiny.

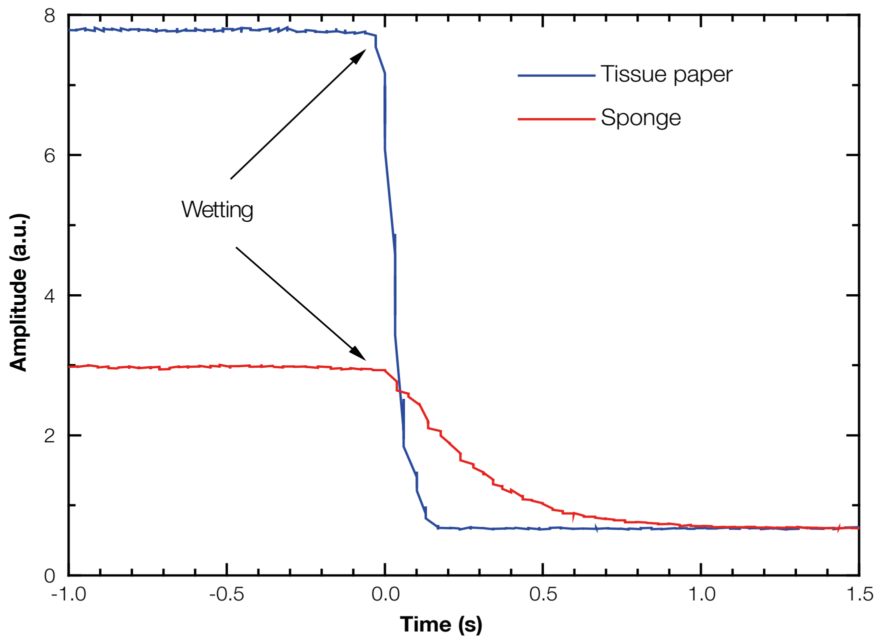


Terahertz imaging of plant leaves.

Ultrafast Dynamics

In fundamental science and industrial monitoring alike, there exists a need for terahertz observations at “extreme” speeds. One example involves the study of protein dynamics in water, where solved biomolecules unfold within milli- or microseconds. In an industrial setting, monitoring the properties of samples on fast conveyor belts calls for truly “ultrafast” means, too, especially if a high spatial resolution is desired.

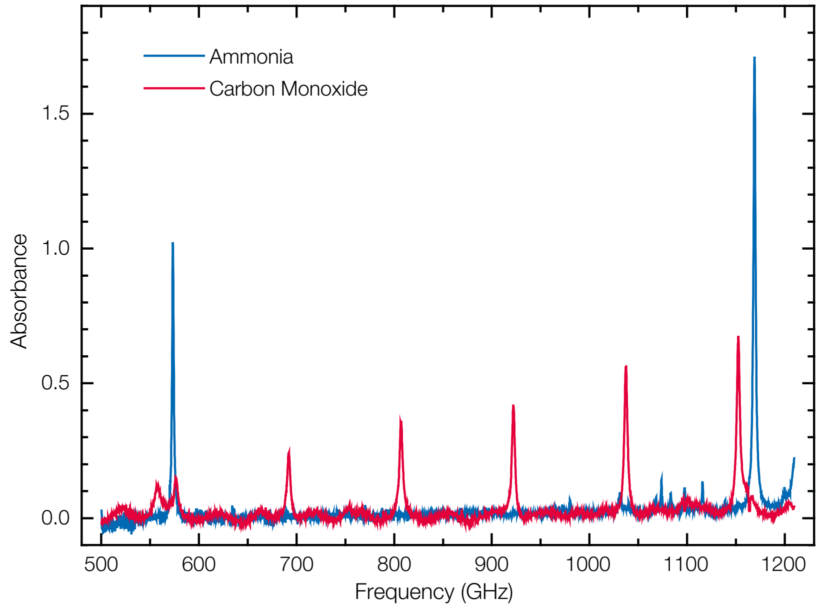
A photoconductive switch hooked up to a femtosecond laser produces tens of millions of terahertz pulses per second. The detection, however, usually includes a delay stage, which limits the acquisition speed to a few 100 pulse traces per second, at most. An alternative approach makes use of a high-bandwidth Schottky receiver: Combined with strong InGaAs emitters, the setup requires neither any delay stage, nor lock-in detection, and consequently, intensity measurements of individual terahertz pulses are achieved. This enables the observation of dynamic processes with a temporal resolution as short as a few nanoseconds.



Absorption dynamics of a sheet of tissue paper and a sponge, wetted with water.

Gas Sensing

Many polar gas molecules possess distinct transitions in the terahertz frequency range. At standard pressure, their linewidths appear pressure-broadened to a few GHz, but at low pressures these absorption lines narrow to single-MHz widths. This opens the possibility to identify individual gases by their terahertz "fingerprint". Whilst gas sensing works in the near-infrared part of the spectrum, too, available lasers offer a limited tuning range, and each gas species may require an individual laser setup. Unique benefits of cw-terahertz spectroscopy include chemical specificity (a single system detects a large number of gases), large bandwidth, MHz-level resolution, and the ability to monitor "inaccessible" settings, such as flames and black smoke.

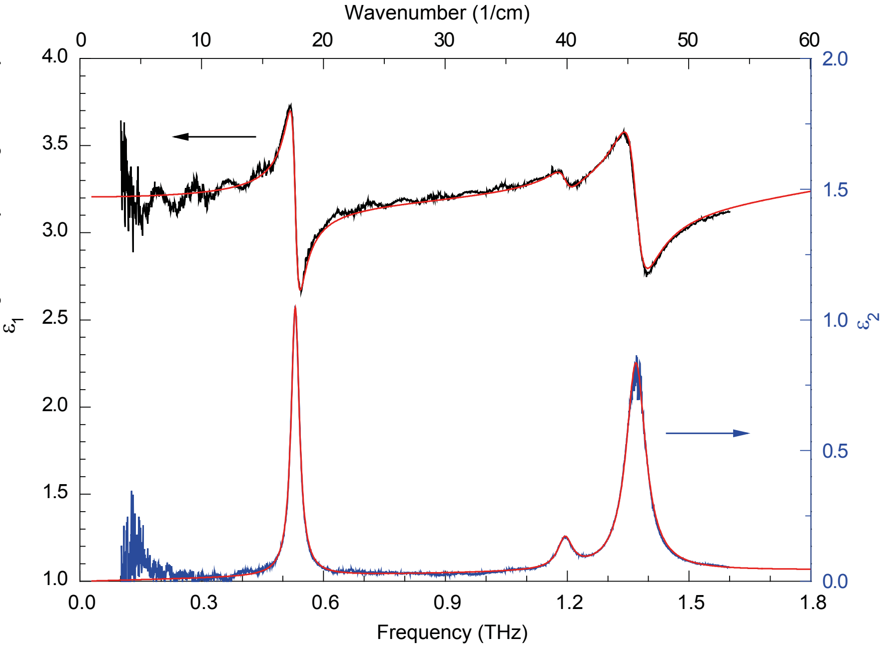


Two application scenarios are industrial process control, and threat detection in public institutions. Demands are high: A monitoring system in a subway station must unambiguously identify hazardous substances in a cluttered background of cleaning agents, glues, engine fumes and paint.

Absorption spectra of ammonia and carbon monoxide, recorded with a TeraScan-1550 system.

Fundamental Physics

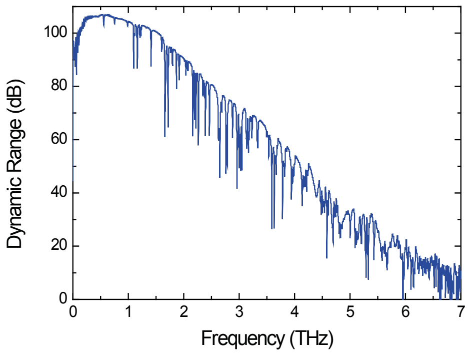
Various applications of terahertz spectroscopy exist, as not only gases, but also many organic solids show absorption signatures at terahertz frequencies. Complementing the information gained from amplitude data, refractive index measurements help unveil the properties of samples: For polymers, the variation of the refractive index with temperature uncovers minute structural changes. For fiber-reinforced plastics, the refractive index yields information on the orientation of the fiber strands. Terahertz spectroscopy provides insights into the molecular dynamics of liquid crystals, and reveals semiconductor parameters such as conductivity and carrier density.



A vibrant field of research involves metamaterials, such as sub-wavelength gratings or split-ring resonators, which exhibit remarkable transmission characteristics, often with narrow signatures. Depending on the design, the resonance frequency changes when the sample is loaded, e.g. with biological probes. The excellent frequency resolution that cw-terahertz systems deliver provides an extra benefit for these studies.

Real part ε_1 (black, left axis) and imaginary part ε_2 (blue, right axis) of the dielectric constant of α-lactose monohydrate, measured with cw-terahertz spectroscopy.

Time-Domain Terahertz Generation



Dynamic range of TOPTICA's time-domain platform **TeraFlash**.

Direct and indirect sources

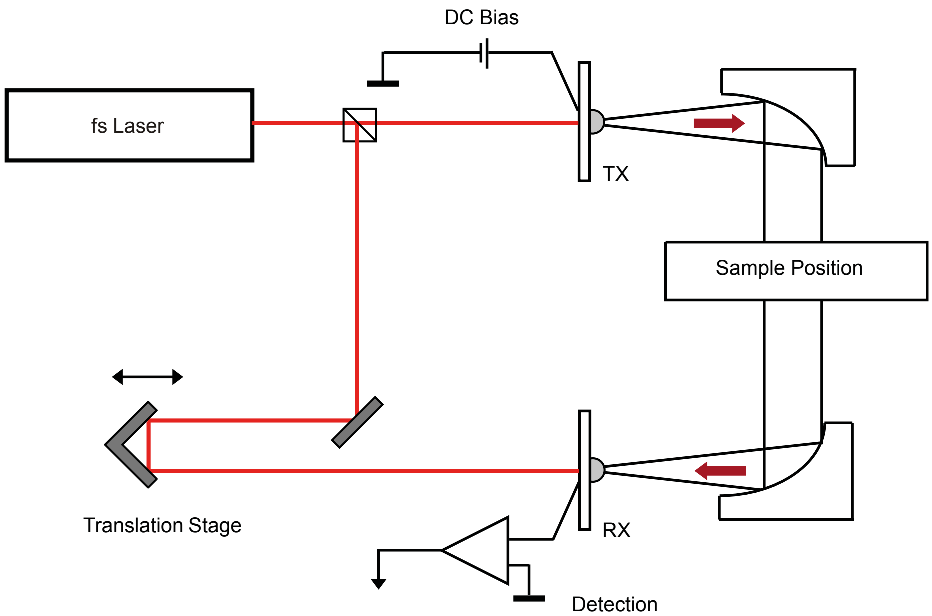
The spectroscopically relevant frequencies from 0.5 – 6 THz prove difficult to access. Electronic sources, such as voltage-controlled oscillators with frequency multipliers, offer power levels in the mW range. However, they become inefficient at terahertz frequencies and provide rather limited frequency tuning. Direct optical sources, like quantum cascade lasers, must operate at cryogenic temperatures and suffer from poor beam profiles and low spectral purity.

Optoelectronic terahertz generation, an expression for indirect methods, involves infrared laser light generating free charge carriers in a semiconductor or organic crystal. The charge carriers are accelerated by internal or external electric fields and the resulting photocurrent becomes the source of the terahertz wave.

The ultrafast approach

Pulsed terahertz radiation is generated with femtosecond lasers. In a typical time-domain setup, the laser pulse is split in two; one part travels to the terahertz emitter, and the other part, after interacting with a sample, travels to the detector.

The ultrashort laser pulses produce a current transient in the emitter and as a result, electromagnetic wave packets with a broad spectrum in the terahertz range. The detector works in a "pump and probe" fashion: The incident terahertz pulse changes the properties of the material (e.g. conductivity or birefringence) and the laser pulse probes this effect. A variable delay stage scans the terahertz wave packet with the much shorter "probe" pulse. A Fourier transform of the terahertz amplitude then reproduces the terahertz spectrum.



Frequency-Domain Terahertz Generation

Give me a beat!

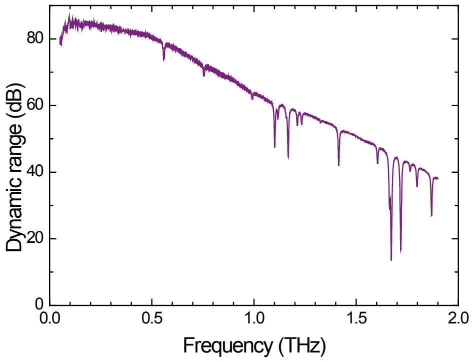
Continuous-wave (cw) terahertz radiation is obtained by optical heterodyning in high-bandwidth photoconductors: The output of two cw lasers is converted into terahertz radiation, exactly at the difference frequency of the lasers.

The core component is the "photomixer," a microscopic metal-semiconductor-metal structure. Near-infrared laser light irradiates this structure at two adjacent frequencies. Applying a bias voltage to the metal electrodes then generates a photocurrent that oscillates at the beat frequency. An antenna structure surrounding the photomixer translates the oscillating photocurrent into the terahertz wave. State-of-the-art photomixers are based on either GaAs or InGaAs/InP and require laser wavelengths below the semiconductor bandgap (i.e. around 0.8 µm or 1.5 µm, respectively).

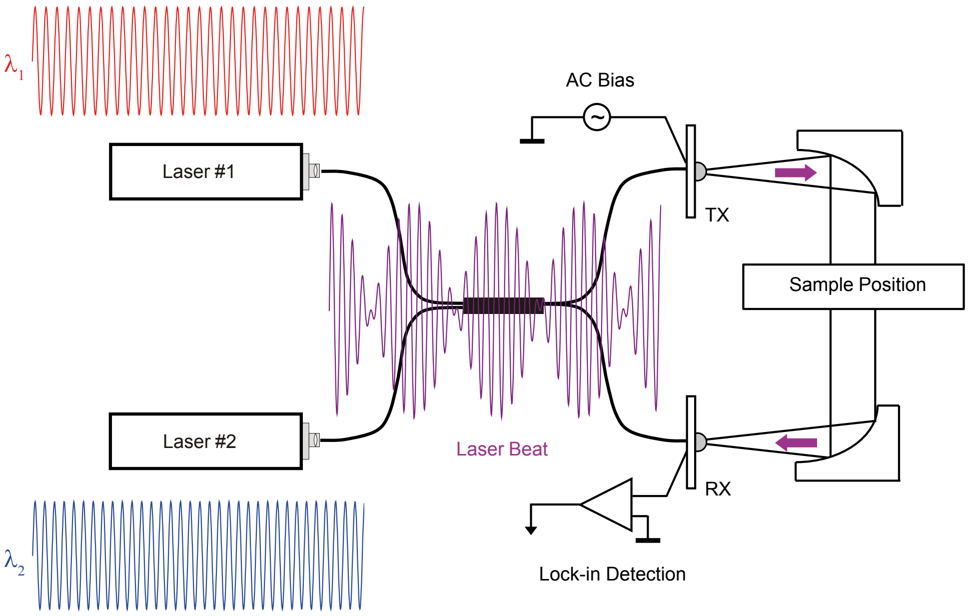
Coherent signal detection

In a coherent detection scheme, a second photomixer serves as terahertz receiver. Similar to the pulsed scenario, both the terahertz wave and the original laser beat illuminate the receiver. The incoming terahertz wave generates a voltage in the antenna while the laser beat modulates the conductivity of the photomixer. The resulting photocurrent, typically in the nanoampère range, is proportional to the amplitude of the incident terahertz electric field. It further depends on the phase difference between the terahertz wave and the optical beat. Spectroscopic measurements commonly take advantage of both amplitude and phase data.

Coherent detection methods offer the advantage of a very high efficiency, and can attain dynamic ranges in excess of 90 dB.



Frequency-domain terahertz spectrum, measured with the **TeraScan 780**.



Product Overview

TOPTICA provides complete systems and components for both time-domain and frequency-domain terahertz generation.

For time-domain applications, the **TeraFlash** sets new standards in terms of dynamic range, bandwidth and measurement speed. Combining TOPTICA's FemtoFiber smart laser technology with state-of-the-art InGaAs antennas, the system achieves a peak dynamic range of more than 90 dB and a bandwidth greater than 5 THz.

For researchers working with GaAs-based photoconductive switches or with organic-crystal emitters, TOPTICA offers a variety of ultrafast fiber lasers, all of which come with superior specifications. Owing to the use of robust saturable absorber mirror technology for mode-locking, all lasers offer turnkey operation and do not require any mechanical alignment.

For frequency-domain terahertz spectroscopy, TOPTICA offers two "TopSeller" systems – **TeraScan 1550** and **TeraScan 780**. Based on precisely tunable DFB lasers, digital control electronics, and latest InGaAs and InGaAs photomixer technology, the TeraScan systems combine ease of use with best-in-class specifications.

A set of modular product packages extends the cw-terahertz product portfolio: The Tuning Range Extension pushes the useable bandwidth out to almost 3 THz, and the Phase Modulation Extension features two fiber stretchers for fast and accurate scanning of the terahertz phase. The packages can be combined and upgraded depending on the requirements of the experiment.

Selected accessories – Schottky diodes, optomechanics and a compact reflection head – are available for both time-domain and frequency-domain systems.

Time-Domain Terahertz Generation


P. 12

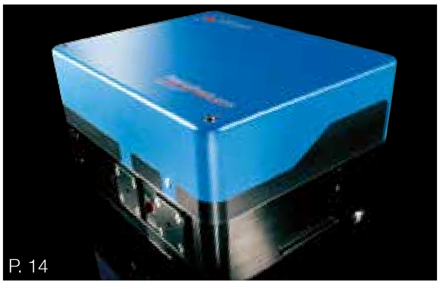
TeraFlash

Time-domain terahertz system with
> 5 THz bandwidth


P. 14

FemtoFiber pro IR

High-power femtosecond fiber laser, emission wavelength 1.5 µm


P. 14

FemtoFiber pro IRS

Femtosecond fiber laser with shortest pulses, < 40 fs


P. 15

FemtoFiber pro NIR

Frequency-doubled femtosecond fiber laser, emission wavelength 780 nm


P. 16

FemtoFErb

Compact and cost-effective fs fiber laser, available at 1.5 µm and 780 nm


P. 17

InGaAs Photoconductive Switches

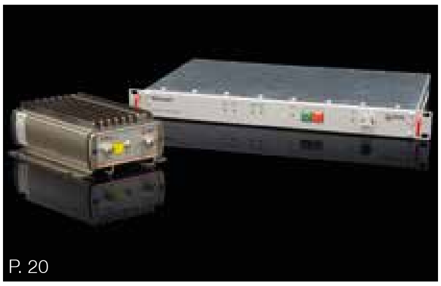
Broadband antennas for pulsed terahertz generation, with Si lens and fiber pigtail

Frequency-Domain Terahertz Generation


P. 18

TeraScan 1550 / 780

Frequency-domain terahertz platform with megahertz-level frequency resolution


P. 20

TeraBeam 1550 / 780

Dual-color DFB lasers with digital driver electronics and precise frequency control


P. 21

Tuning Range Extension

Additional diode laser, increases the use-able bandwidth beyond 2 THz


P. 22

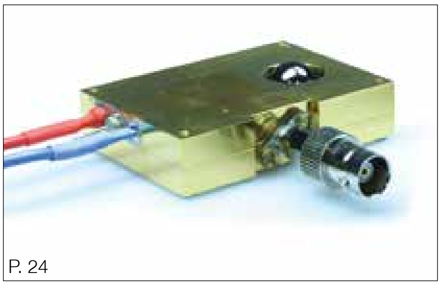
Phase Modulation Extension

Twin fiber stretcher for fast and accurate terahertz phase modulation


P. 23

GaAs / InGaAs Photomixers

Top-quality photomixers for cw-terahertz generation, with SM/PM fiber pigtail


P. 24

Schottky Receivers

Terahertz power detectors, suitable for imaging or single-pulse detection

TeraFlash

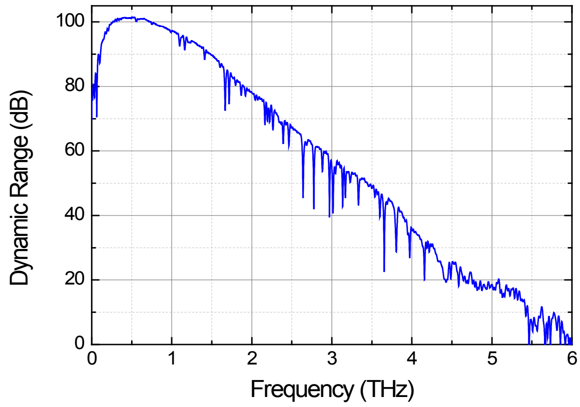
Versatile Time-Domain Terahertz Platform

Key Features

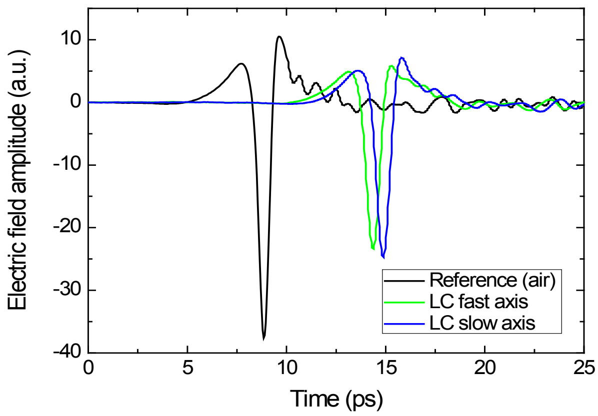
- Reliable 1.5 µm telecom technology
- Fiber-coupled InGaAs photoconductive switches
- 5 THz bandwidth, > 90 dB peak dynamic range

The TeraFlash system combines TOPTICA's FemtoFErb fiber laser and state-of-the-art InGaAs photoconductive switches into a table-top terahertz platform, based on mature 1.5 µm telecom technology. Owing to a highly precise voice-coil delay stage with a timing resolution of 1.3 fs, the TeraFlash achieves a peak dynamic range of more than 90 dB.

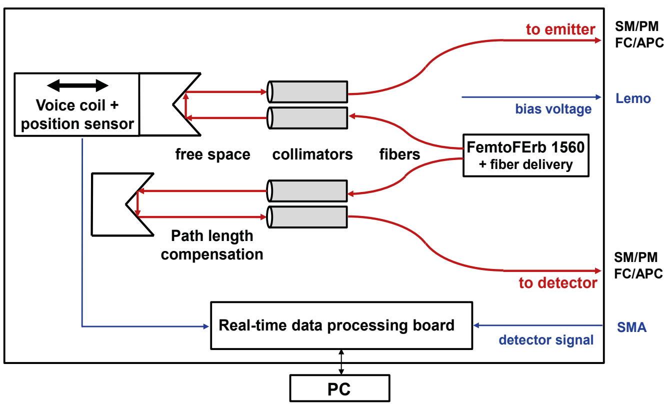
The control software can flexibly adjust the scan time and the number of averages: In "precise scan" mode, the system attains a bandwidth of 5 THz, whilst in "fast scan" mode, a pulse trace is acquired in only 50 ms. Equipped with SM/PM fiber pigtails, the antenna modules can be flexibly arranged according to the requirements of the experiment in question.



TeraFlash spectrum. The peak dynamic range reaches 90 dB with 1000 averages, and 100 dB with 10000 averages.



Pulse traces of a birefringent liquid crystal polymer (Ticona A950) and a reference trace in air.



Schematic diagram of the TeraFlash. Blue lines depict electric signals, red lines the optical signals.

Specifications

Specifications TeraFlash	
Components	Femtosecond laser, SM/PM fiber delivery, 2 delay stages (stationary / moving), 2 InGaAs photoconductive switches, electronics for data acquisition, laptop computer
Laser	FemtoFErb THz FD6.5
Laser wavelength	1560 nm
Laser pulse width	< 60 fs (< 45 fs typ.)
Laser repetition rate	100 MHz
Terahertz emitter	#EK-000781, InGaAs/InP photoconductive switch with 100 µm strip-line antenna
Terahertz receiver	#EK-000782, InGaAs/InP photoconductive switch with 25 µm dipole antenna, 10 µm gap
Antenna package	Cylindrical, ⌀ 25 mm Integrated Si lens and SM/PM fiber pigtail (1 m)
Terahertz spectral range	0.1 - 5 THz
Average terahertz power	> 50 µW (60 µW typ.)
Peak dynamic range	> 90 dB (95 dB typ.)
Delay stage	Computer-controlled mechanical delay + fast voice coil
Delay stage scan	20 - 200 ps
Frequency resolution	< 5 GHz @ 200 ps scan < 40 GHz @ 25 ps scan
Acquisition rate	Precise scan: 60 s/spectrum, 70 ps delay, 5 THz bandwidth, peak dynamic range > 90 dB Fast scan: 50 ms/spectrum, 50 ps delay, 3 THz bandwidth, peak dynamic range > 60 dB Intermediate settings possible
Maximum measurement speed	50 traces/s (20 ps delay)
Useable terahertz path length	15 - 80 cm, adjustable via stationary delay
Computer interface	Ethernet
Control software	LabView-based GUI, included
Size (H x W x D)	180 x 450 x 560 mm

Further reading:

N. Vieweg et al., *Terahertz-time domain spectrometer with 90 dB peak dynamic range;* J Infrared Milli. Terahz. Waves **35** (2014) 823-832.

FemtoFiber pro IR / IRS

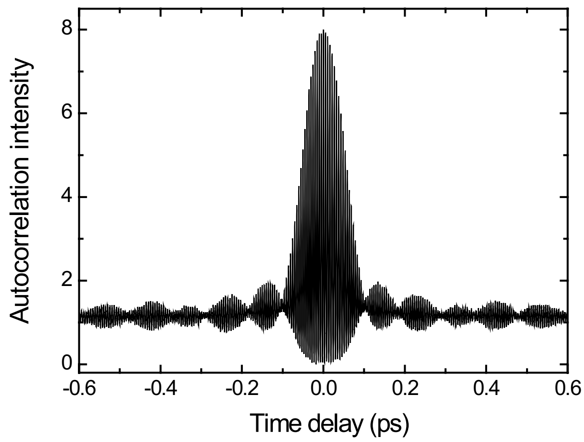
High-Power Infrared Femtosecond Fiber Lasers

Key Features

- Er:fiber lasers with mode-locked oscillator and amplifier
- FemtoFiber pro IR: Highest power (> 350 mW)
- FemtoFiber pro IRS: Shortest pulses (< 40 fs)

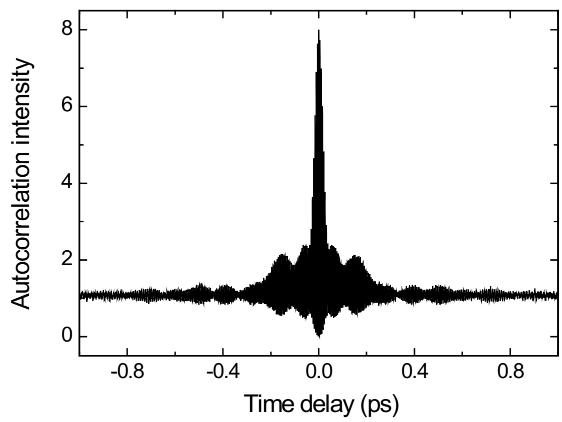
The FemtoFiber pro IR is the base unit of TOPTICA's Femto Fiber pro series. It comprises a robust, SAM mode-locked oscillator and a power amplifier, and provides an average power of > 350 mW. The pulse duration is below 100 fs.

The short-pulse version FemtoFiber pro IRS features an additional non-linear fiber to generate pulses of less than 40 fs. The pulse width can be controlled by an automated feedback loop. Both lasers employ an alignment-free, polarization-maintaining all-fiber setup. They come in a compact footprint that doesn't require water or air cooling. Pulse durations and power levels are well-suited for terahertz generation in organic crystals such as DAST, DSTMS or OH1.



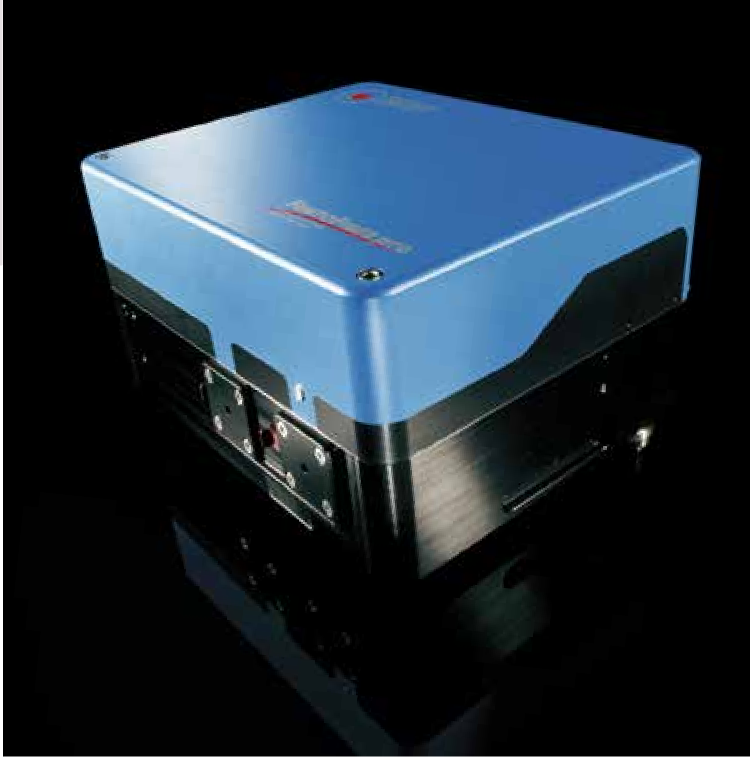
Autocorrelation pulse width of FemtoFiber pro IR: < 100 fs at 1560 nm.

Laser	**FemtoFiber pro IR**	**FemtoFiber pro IRS**
Wavelength	1560 nm	1570 nm
Laser output power	> 350 mW	> 200 mW (250 mW typ.)
Pulse width	< 100 fs	< 40 fs (30 fs typ.)
Repetition rate	80 MHz (optional: 40 MHz)	80 MHz
Beam shape	TEM_{00}, $M^2 < 1.2$	
Beam diameter ($1/e^2$)	3.5 mm typ.	1.8 mm typ.
Beam divergence	< 2 mrad	< 1 mrad
Polarization	Linear, > 95%, horizontal	Linear, > 95%, vertical
Output	Free-space	
Laser size (H x W x D) and weight	150 x 280 x 230 mm, < 10 kg	
Control unit size (H x W x D) and weight	140 x 235 x 315 mm, < 4.5 kg	
Computer interface	Ethernet, USB, RS 232	
Pump diode warranty	5000 hrs or 1 year (whatever comes first)	



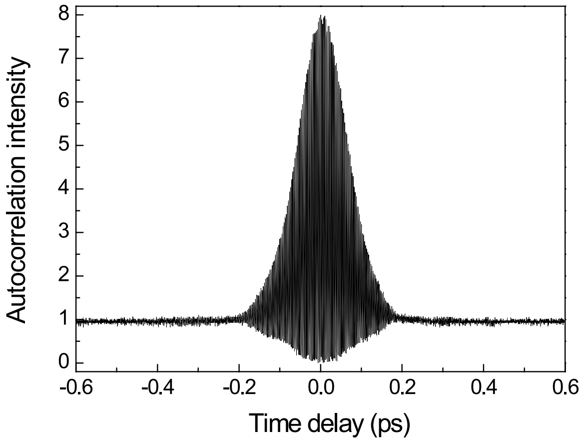
Autocorrelation pulse width of FemtoFiber pro IRS: < 30 fs at 1560 nm.

FemtoFiber pro NIR
Near-Infrared Femtosecond Fiber Laser

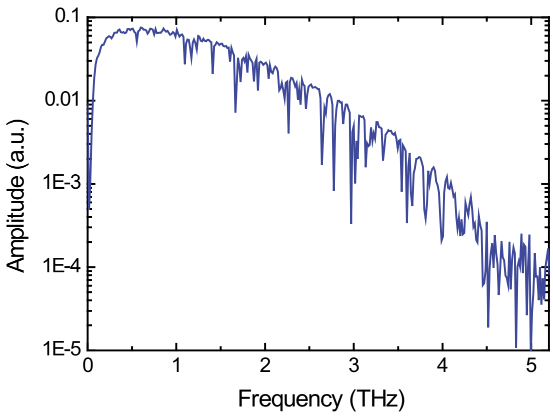


Key Features

- Er:fiber lasers with second-harmonic-generation stage
- Average power > 140 mW @ 780 nm
- Output switchable between 780 nm and 1560 nm



Autocorrelation pulse width of FemtoFiber pro NIR: < 100 fs at 780 nm.



THz spectrum, acquired with the FemtoFiber pro NIR and GaAs antennas.

The FemtoFiber pro NIR includes an Erbium fiber laser with a SAM mode-locked oscillator, a power amplifier, and a second harmonic generation (SHG) stage. It offers both the fundamental and the frequency-doubled output, and the user selects the wavelength with a manual switch. In a customized design, the laser emits both beams simultaneously from separate output ports. A motorized prism compressor optimizes the pulse characteristics at either wavelength, attaining pulse durations below 100 fs.

The FemtoFiber pro NIR provides an ideal laser source for terahertz generation via GaAs-based photoconductive switches or for hybrid systems with an organic emitter (DAST, DSTMS) and a GaAs detector.

Laser	FemtoFiber pro NIR	
Wavelength	780 nm (Output 1)	1560 nm (Output 2)
Laser output power	> 140 mW	> 350 mW
Pulse width	< 100 fs	
Repetition rate	80 MHz (optional: 40 MHz)	
Beam shape	TEM_{00}, $M^2 < 1.2$	
Beam diameter ($1/e^2$)	1.2 mm typ.	3.5 mm typ.
Beam divergence	< 1 mrad	< 2 mrad
Polarization	Linear, > 95%, horizontal	Linear, > 95%, vertical
Output	Free-space	
Laser size (H x W x D) and weight	150 x 280 x 230 mm, < 10 kg	
Control unit size (H x W x D) and weight	140 x 235 x 315 mm, < 4.5 kg	
Computer interface	Ethernet, USB, RS 232	
Pump diode warranty	5000 hrs or 1 year (whatever comes first)	

FemtoFErb 1560 / 780

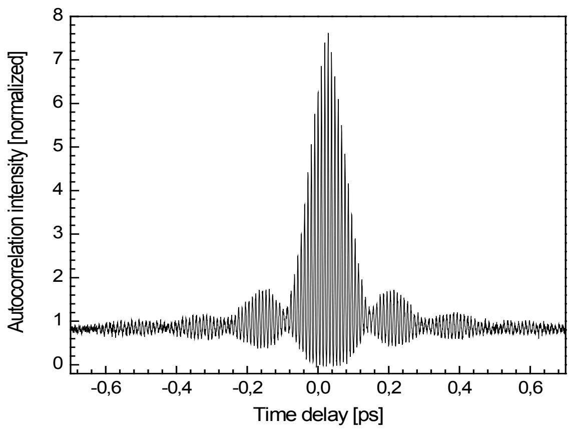
Compact Ultrafast Fiber Laser

Key Features

- Highly compact femtosecond laser, optics and electronics in just one box
- Optional SM/PM fiber delivery @ 1560 nm
- Ideal lasers for GaAs or InGaAs photoconductive switches

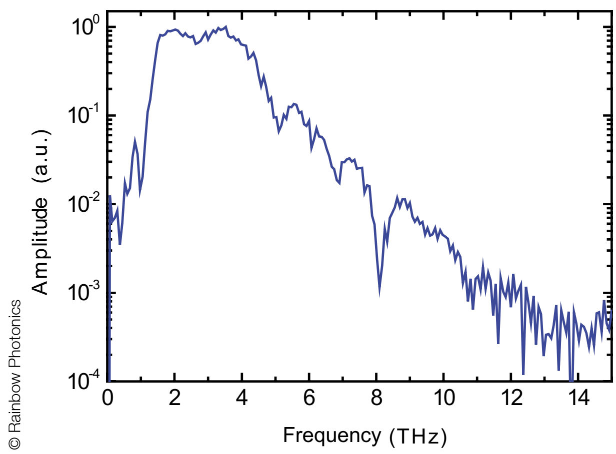
TOPTICA's FemtoFErb laser family consists of highly compact Erbium fiber lasers, with the electronics integrated in the laser head. At the fundamental wavelength of 1560 nm, TOPTICA offers two different models, either with a short fiber output (FemtoFErb 1560 THz), or with a detachable, 6.5 m SM/PM patchcord (FemtoFErb THz FD6.5). Both lasers generate narrow pulses with typical pulse widths of only 50 fs. Both models also employ TOPTICA's proprietary QuTe technology, which protects sensitive InGaAs antennas from dangerous Q-switch pulses.

The frequency-doubled laser FemtoFErb 780 provides an ideal match for GaAs antennas. It features a free-beam output with an excellent TEM_{00} beam profile.



Typical autocorrelation pulse width of a FemtoFErb laser with fiber delivery (model FemtoFErb THz FD6.5): 45 fs.

Laser	FemtoFErb 1560 THz	FemtoFErb THz FD6.5	FemtoFErb 780
Wavelength	1560 nm	1560 nm	780 nm
Laser output power	> 120 mW (140 mW typ.)	> 80 mW (90 mW typ.)	> 50 mW
Pulse width	< 80 fs (50 fs typ.)	< 60 fs (45 fs typ.)	< 100 fs (90 fs typ.)
Repetition rate	100 MHz		
Beam shape	TEM_{00}, M² < 1.2		
Beam diameter (1/e²)	N.A.	N.A.	1.6 mm typ.
Beam divergence	N.A.	N.A.	< 1.5 mrad
Polarization	SM/PM fiber: PER > 20 dB typ.	SM/PM fiber: PER > 15 dB typ.	Linear, > 95%, vertical
Output	SM/PM fiber pigtail, 20 cm, FC/APC	SM/PM fiber patchcord, 6.5 m, FC/APC	Free-space
QuTe	Q(u)-Switch Termination, protection mechanism included		--
Laser size (HxWxD) and weight	70 x 120 x 200 mm, < 2.2 kg		
Control unit	Included in laser head		
Computer interface	USB		
Pump diode warranty	5000 hrs or 1 year (whatever comes first)		



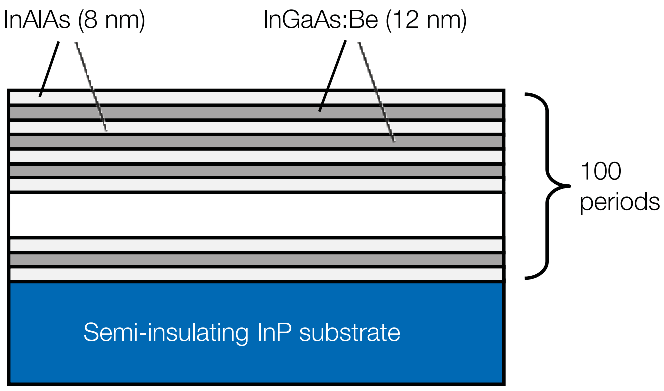
Terahertz amplitude spectrum, acquired with the FemtoFErb 1560 and a DSTMS crystal.

Photoconductive Switches

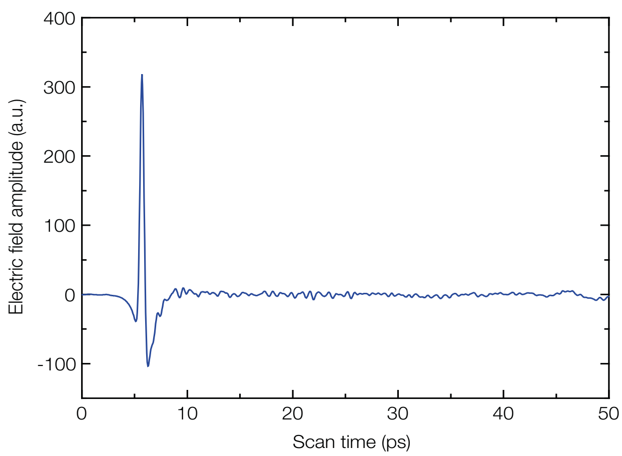
InGaAs Antennas for Time-Domain Terahertz Generation & Detection

Key Features

- Compact modules with SM/PM fiber pigtail and silicon lens
- High terahertz power: > 50 µW average
- Large bandwidth: > 5 THz



Multi-layer structure of the emitter and receiver modules.



Pulse trace of an InGaAs photoconductive switch.

Pulsed terahertz generation with leading-edge technology: Fiber-pigtailed InGaAs antennas provide more than 50 µW average power and their bandwidth spans as much as 5 THz. The design, developed by Fraunhofer Heinrich-Hertz Institute (HHI, Berlin/Germany), uses a multi-stack of InGaAs absorber layers and InAlAs trapping layers to reduce the dark conductivity of the semiconductor and maximize the efficiency of the device.

The emitter and detector modules feature a strip-line and a dipole antenna, respectively, and are packaged with a Silicon lens and SM/PM fiber. These photoconductive switches make up the core component of TOPTICA's TeraFlash, but are available as individual modules too.

	Photoconductive Switches
Terahertz emitter	#EK-000781, photoconductive switch with 100 µm strip-line antenna
Terahertz receiver	#EK-000782, photoconductive switch with 25 µm dipole antenna, 10 µm gap
Semiconductor material	Multi-layer structure of InGaAs and InAlAs on InP
Excitation wavelength	1.5 µm
Emitter / receiver bandwidth	> 5 THz
Average terahertz power	> 50 µW (typ. 60 µW) @ 20 mW laser power
Package	Cylindrical, 25 mm Integrated Si lens and SM/PM fiber pigtail
Recommended operating conditions	Laser power: 20 mW average Max. bias +120 V (unipolar, emitter), ± 3 V (receiver, only for testing)
Bias modulation	Possible, up to 100 kHz

TeraScan 780 / 1550

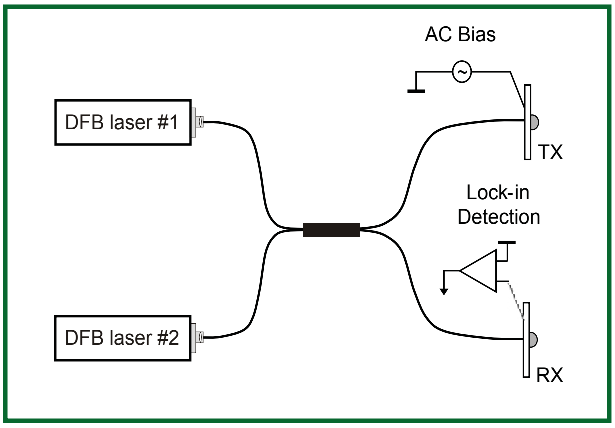
TOPSellers for Frequency-Domain Spectroscopy

Key Features

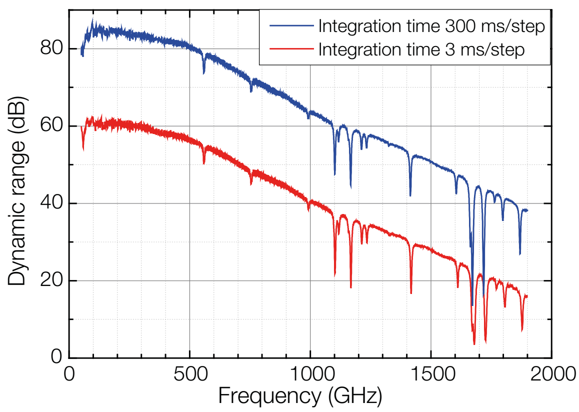
- Complete systems with high-end GaAs or InGaAs photomixers
- Highest bandwidth: TeraScan 780
- Highest dynamic range: TeraScan 1550

TOPTICA's TeraScan platforms are "TOPSeller" configurations for frequency-domain terahertz spectroscopy. The systems combine mature DFB diode lasers with state-of-the-art GaAs or InGaAs photomixer technology. The TeraScan 780 offers an outstanding bandwidth, owing to the wide tuning range of carefully selected near-infrared DFB diodes. The TeraScan 1550, in turn, sets new benchmarks in terms of terahertz power and dynamic range. Both systems feature TOPTICA's proprietary "DLC smart" control electronics, and an intuitive software interface.

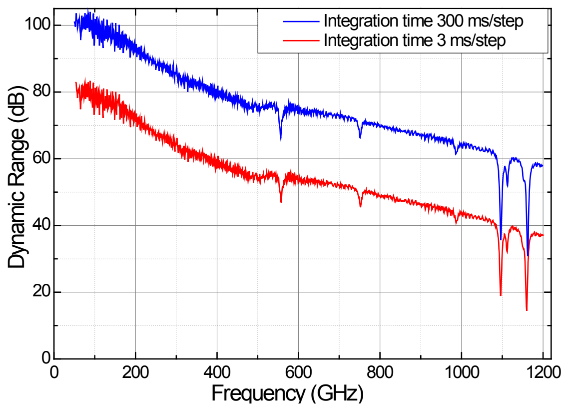
The TeraScan systems lend themselves both as versatile starter packages for cw-terahertz research, and as base units for system integrators.



Schematic of TeraScan systems.



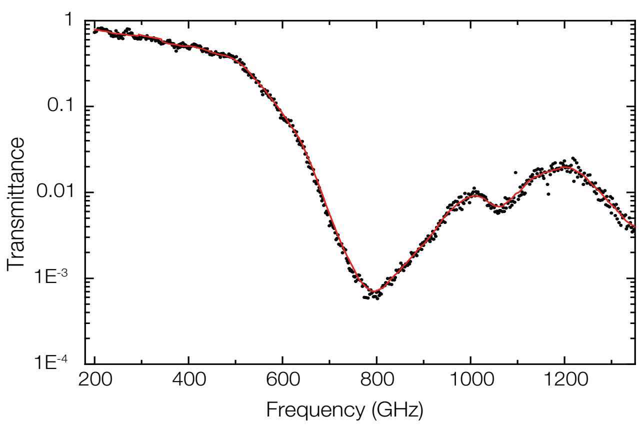
Dynamic range of a TeraScan 780 system.
The dips are absorption lines of water vapor.



Dynamic range of a TeraScan 1550 system.

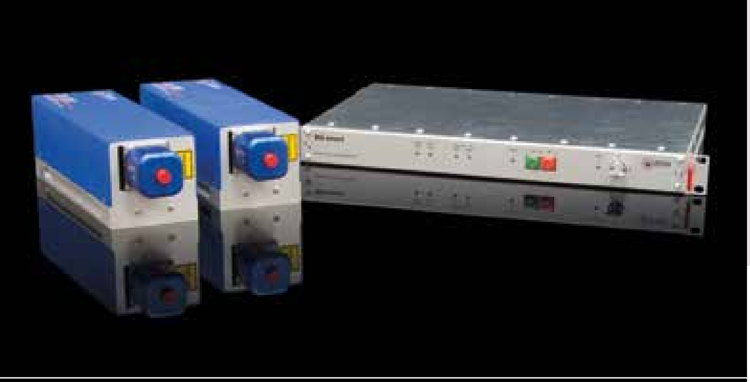
Specifications

Specifications	**TeraScan 780**	**TeraScan 1550**
Lasers	TeraBeam 780	TeraBeam 1550
Difference frequency tuning	1.8 THz (2.0 THz typ.)	1.2 THz (up to 2.7 THz with Tuning Range Extension)
Tuning speed	Up to 100 GHz / sec	
Frequency accuracy	2 GHz absolute, < 10 MHz relative	
Terahertz emitter	#EK-000831, GaAs photomixer	#EK-000724, high-bandwidth InGaAs photodiode
Terahertz receiver	#EK-000832, GaAs photomixer	#EK-000725, InGaAs photomixer
Antenna type	Log-spiral	Bow-tie
Terahertz polarization	Circular	Linear
Emitter and receiver package	Cylindrical, ø 1" Integrated Si lens and SM/PM fiber pigtail	Cylindrical, ø 25 mm Integrated Si lens and SM/PM fiber pigtail
Terahertz power (typ.)	2 µW @ 100 GHz 0.3 µW @ 500 GHz	65 µW @ 100 GHz 5 µW @ 500 GHz
Terahertz dynamic range (300 ms integration time)	80 dB @ 100 GHz 70 dB @ 500 GHz	90 dB @ 100 GHz 70 dB @ 500 GHz
Laser size (H x W x D) and weight	Two laser heads, each with dimensions 80 x 80 x 270 mm, 2 kg	60 x 120 x 165 mm, 1 kg
Control unit	DLC smart	
Controller size (H x W x D) and weight	50 x 480 x 290 mm, 4 kg	
Computer interface	Ethernet	
Software	Control software with GUI + Remote command interface	
Key advantages	High bandwidth with one set of lasers	High terahertz power, compact laser unit



Absorption spectrum of the plastic explosive RDX, recorded with the TeraScan 780.

Further reading:
A. Roggenbuck et al., *Coherent broadband continuous-wave terahertz spectroscopy on solid-state samples;* New J. Phys. **12** (2010) 43017-43029.
A.J. Deninger et al., *2.75 THz tuning with a triple-DFB laser system at 1550 nm and InGaAs photomixers;* J Infrared Milli. Terahz. Waves **36** (2015) 269-277.



TeraBeam 780 / 1550

DFB Lasers for cw Terahertz Generation

Key Features

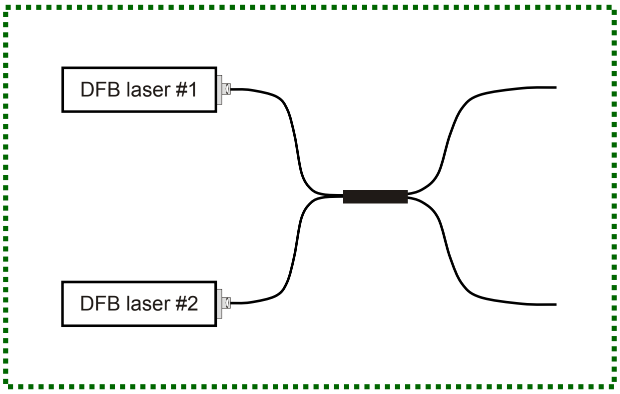
- Two DFB lasers with microprocessor-based frequency control
- Available wavelengths: 780 nm and 1.5 µm
- Frequency accuracy: 2 GHz absolute, < 10 MHz relative

Each TeraBeam system comprises two distributed feedback (DFB) lasers with built-in optical isolators and fiber-optic beam combination. Available at 780 nm and 1.5 µm, the TeraBeam matches the excitation wavelengths of GaAs and InGaAs terahertz emitters, respectively.

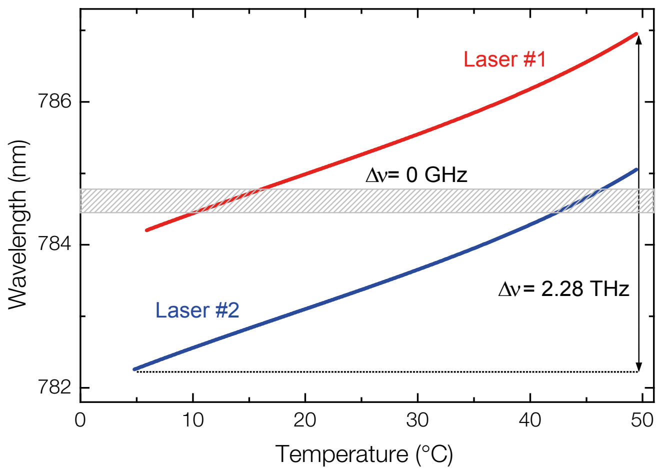
TOPTICA carefully selects the laser diodes, paying close attention to their mode-hop-free tuning range, and records precise tuning curves (wavelength vs. temperature), which are stored in a lookup table. The DLC Smart addresses the thermo-electric coolers of both DFB diodes in order to tune to a desired terahertz frequency. The minimum step size is on the 1 MHz level, which corresponds to a temperature change of only 40 µK per laser.

Specifications	TeraBeam 780	TeraBeam 1550
Laser wavelengths	783 nm + 785 nm	1533 nm + 1538 nm
Laser power	> 40 mW per two-color fiber output	> 30 mW per two-color fiber output
Difference frequency tuning	0 - 1.8 THz (2.0 THz typ.)	0 - 1.2 THz (up to 2.7 THz with Tuning Range Extension)
Tuning speed	Up to 100 GHz / sec	
Frequency accuracy	2 GHz absolute, < 10 MHz relative	
Frequency stability per laser*	Typ. 20 MHz RMS, 100 MHz p-p @ 5 hrs	
Laser size (H x W x D) and weight	Two laser heads, each with dimensions 80 x 80 x 270 mm, 2 kg	60 x 120 x 165 mm, 1 kg
Control unit	DLC Smart	
Controller size (H x W x D) and weight	50 x 480 x 290 mm, 4 kg	
Laser diode warranty	5000 hrs or 2 years (whatever comes first)	

*At constant environmental conditions



Schematic of TeraBeam.



Frequency calibration of a TeraBeam 780 system. The wavelengths of the two DFB lasers overlap at approx. 784.6 nm (shaded bar). By heating laser #1 and cooling laser #2, the difference frequency increases up to 2.3 THz.

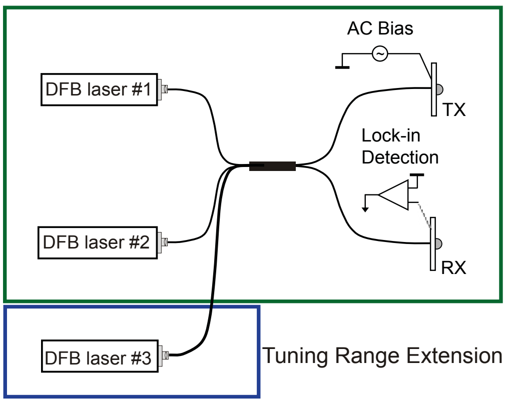
Further reading:
D. Stanze et al., *Compact cw terahertz spectrometer pumped at 1.5 µm wavelength;* J Infrared Milli. Terahz. Waves **32** (2011) 225-232.

Tuning Range Extension

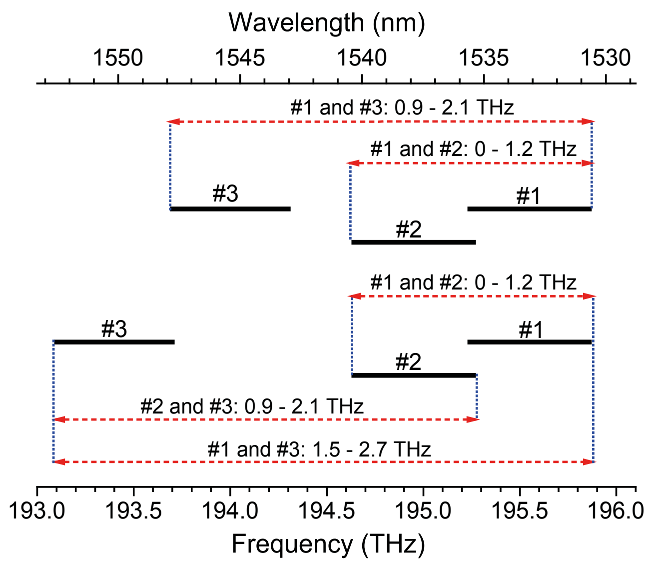
Triple-Laser Systems – Frequencies up to 2.7 THz

Key Features

- Third laser head provides access to higher terahertz frequencies
- Two versions available: DC to 2.0 THz or DC to 2.7 THz
- Accurate frequency calibration for each 2-laser-subset provided



Schematic of TeraScan (green) with Tuning Range Extension (blue).



Combinations of lasers used for the Tuning Range Extension to 2.0 THz (top) and 2.7 THz (bottom).

Owing to the efficiency of the latest InGaAs photomixers, TOPTICA has been able to push the frequency limits of frequency-domain spectrometers. Whilst one DFB laser at 1.5 µm offers a continuous tuning range of approximately 600 GHz, a combination of three lasers covers the entire frequency range from DC to 2.0 THz, or – using a more elaborate set of combinations – even up to 2.7 THz.

TOPTICA's "Tuning Range Extension" thus provides access to a frequency range that used to be beyond reach with commercial frequency-domain spectrometers. The frequency accuracy achieved with TOPTICA's DLC Smart controller is so high that spectra obtained with different subsets of lasers can easily be "stitched together".

Specifications	THz Tuning Extension 2.0	THz Tuning Extension 2.7
Base system	TeraBeam 1550 (λ_1 = 1533 nm, λ_1 = 1538 nm)	
3rd laser	λ_3 = 1545 nm	λ_3 = 1550 nm
Difference frequency tuning	**0 - 2.0 THz** · 0 – 1.2 THz with lasers #1 and #2 („TeraBeam") · 0.9 - 2.0 THz with lasers #1 and #3	**0 - 2.7 THz** · 0 - 1.2 THz with lasers #1 and #2 („TeraBeam") · 0.9 - 2.0 THz with lasers #2 and #3 · 1.5 - 2.7 THz with lasers #1 and #3
Laser power	See TeraBeam 1550	
Tuning speed	See TeraBeam 1550	
Frequency accuracy	See TeraBeam 1550	
Laser size (H x W x D) and weight	Two laser heads, each with dimensions 60 x 120 x 165 mm, 1 kg	
Control unit	DLC Smart	
Controller size (H x W x D) and weight	480 x 290 x 50 mm, 4 kg	
Laser diode warranty	5000 hrs or 2 years (whatever comes first)	

Further reading:

A.J. Deninger et al., *2.75 THz tuning with a triple-DFB laser system at 1550 nm and InGaAs photomixers;* J Infrared Milli. Terahz. Waves **36** (2015) 269-277.

Phase Modulation

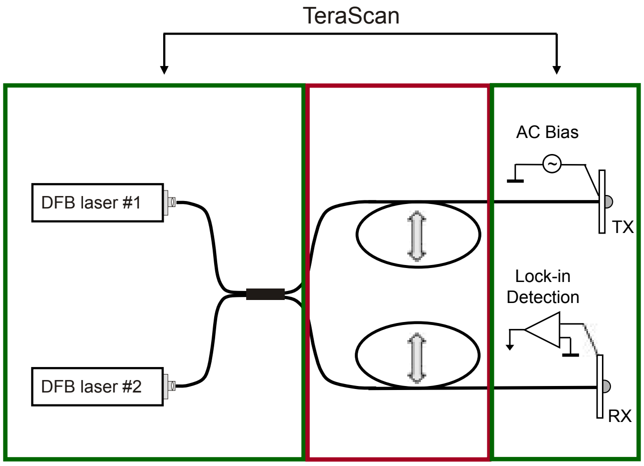
Twin Fiber Stretcher with HV Driver

Key Features

- Fast and accurate modulation of the terahertz phase
- Twin fiber stretcher with piezo actuators and HV driver
- Path length modulation up to 3 mm @ 1 kHz

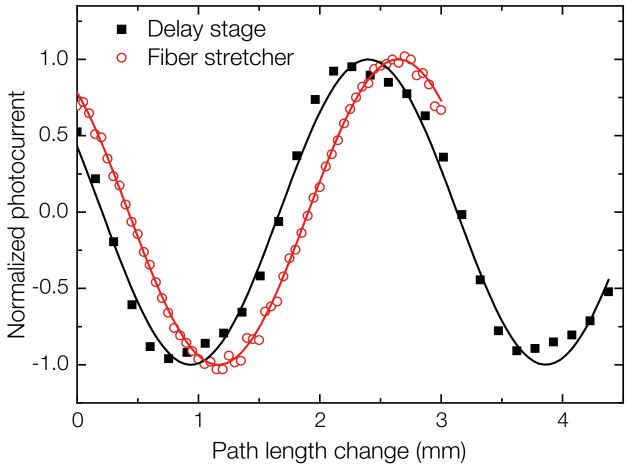
Cw terahertz spectroscopy based on photomixing offers the attractive feature of detecting both amplitude and phase of the terahertz wave. Determining the phase requires a modulation of the optical path length, or of the terahertz frequency. The Phase Modulation Extension provides a fast and accurate technique to scan the terahertz phase by using a symmetric setup with two fiber stretchers wound around piezo actuators. The twin-fiber concept not only doubles the modulation amplitude, but also increases the thermal stability of the setup.

The Phase Modulation Extension is available at 780 nm and 1.5 µm, perfectly fitting the respective TeraScan systems.



Schematic of TeraScan (green) with Phase Modulation Extension (red).

Specifications	THz Phase Mod / NIR	THz Phase Mod / IR
Concept	Twin fiber stretcher with piezo actuators	
Wavelength	780 nm, as defined by TeraScan 780 / TeraBeam 780	1.5 µm, as defined by TeraScan 1550 / TeraBeam 1550
Difference frequency tuning	See TeraScan / TeraBeam systems	
Difference frequency resolution	See TeraScan / TeraBeam systems. Complete amplitude + phase information available at maximum resolution.	
Fibers	2 x 60 m, SM/PM fibers	
Max. path length modulation	3 mm @ 1 kHz	
HV amplifier	Included	
Software	Included, part of control program	



Terahertz photocurrent, measured with fiber stretchers (red circles) or a mechanical delay stage in the terahertz path (black squares). The delay-stage scan deviates from a cosine fit due to standing waves. The fiber-stretcher scan yields a perfect cosine curve.

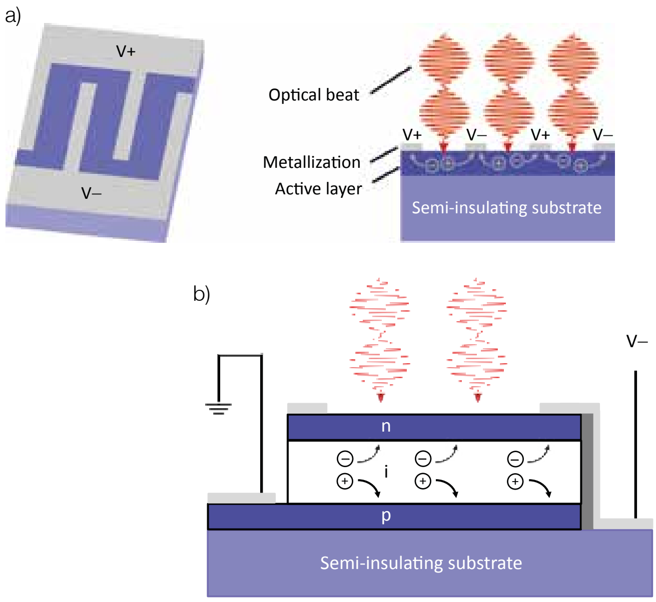
Further reading:
A. Roggenbuck et al., *Using a fiber stretcher as a fast phase modulator in a continuous wave terahertz spectrometer;* JOSA B **29** (2012) 614-620.

Photomixers

Top-Quality Modules for Frequency-Domain Terahertz Generation and Detection

Key Features

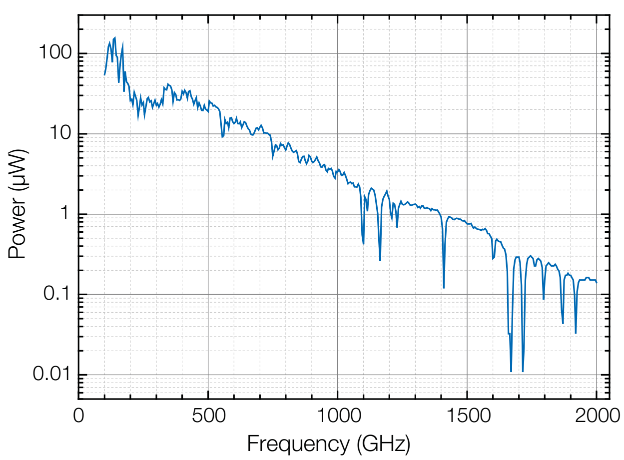
- Cutting-edge GaAs (780 nm) and InGaAs (1.5 µm) photomixers
- Fully-packaged modules with silicon lens and SM/PM fiber pigtail
- Up to 65 µW output power



(a) Top view and cross section (right) of a planar photomixer with interdigitated finger structure. (b) Cross-section of a p-i-n photodiode. V+ and V- denote the applied bias voltage.

Having teamed up with some of the world's leading terahertz research institutes, TOPTICA is able to offer top-quality GaAs and InGaAs photomixers. Both material systems have their own merits. Systems with GaAs photomixers provide high bandwidths, owing to the wide continuous tuning range of 780 nm lasers. InGaAs emitters, on the other hand, generate power at record levels and take advantage of mature yet inexpensive 1.5 µm telecom technology.

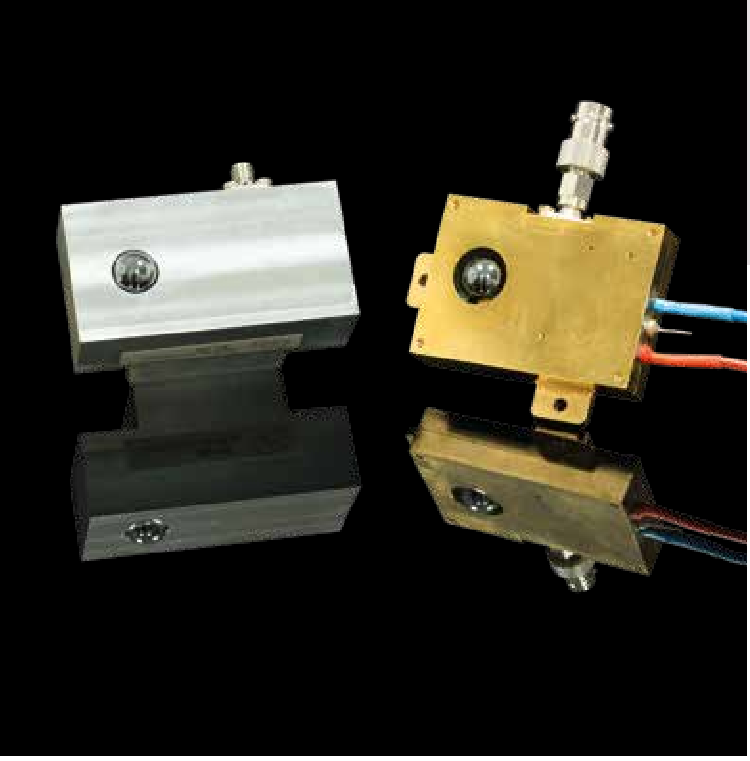
All of TOPTICA's photomixer modules come equipped with a Silicon lens, an electric connector and SM/PM fiber pigtail. The all-fiber design eliminates the need for time-consuming laser beam alignment, and enables an easy and flexible integration into any terahertz assembly.



Output power spectrum of an InGaAs photodiode emitter.

Specifications	GaAs Modules	InGaAs Modules
Terahertz emitter	#EK-000831, GaAs photomixer	#EK-000724, high-bandwidth InGaAs p-i-n photodiode
Terahertz receiver	#EK-000832, GaAs photomixer	#EK-000725, InGaAs photomixer
Excitation wavelength	0.8 µm	1.5 µm
Antenna type	Log-spiral	Bow-tie
Terahertz polarization	Circular	Linear
Emitter and receiver package	Cylindrical, ø 1" Integrated Si lens and SM/PM fiber pigtail	Cylindrical, ø 25 mm Integrated Si lens and SM/PM fiber pigtail
Emitter and receiver bandwidth	Approx. 3 THz	
Terahertz power (typ.)	2 µW @ 100 GHz 0.3 µW @ 500 GHz	65 µW @ 100 GHz 5 µW @ 500 GHz
Terahertz dynamic range	80 dB @ 100 GHz 70 dB @ 500 GHz	90 dB @ 100 GHz 70 dB @ 500 GHz
(300 ms integration time)	0.8 µm	1.5 µm

Further reading:
A. Deninger: *State-of-the-art in terahertz continuous wave photomixer systems,* In: D. Saeedkia (Edt.), *Handbook of Terahertz Technology*, Woodhead Publishing Series in Electronic and Optical Materials (2013).



Accessories

Schottky Receivers

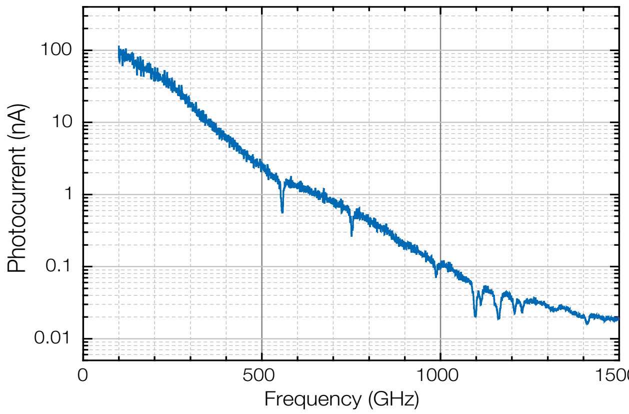
Key Features

- Terahertz power detector
- Ideally suited for terahertz imaging
- High-bandwidth version measures individual terahertz pulses

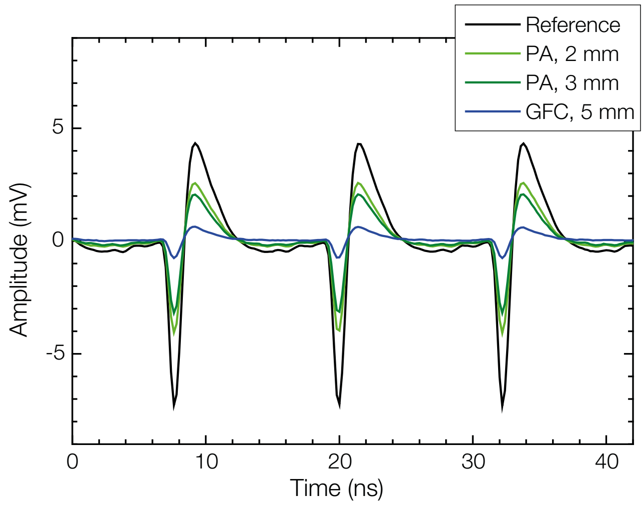
Schottky diodes work as incoherent receivers (i.e., power detectors) for both pulsed and cw-terahertz radiation. In contrast to photomixer receivers or photoconductive switches, they are insensitive to the terahertz phase, but accomplish a direct measurement of the field intensity of the incident terahertz wave. This brings significant advantages for terahertz imaging, which benefits from both speed and sensitivity of the Schottky receivers.

A special high-bandwidth version lends itself for terahertz communication, or for the study of ultrafast processes – owing to its capability of resolving the amplitudes of individual terahertz pulses, even at typical repetition rates of femtosecond fiber lasers!

Specifications	#EK-000933 ("High Responsivity")	#EK-000961 ("High Bandwidth")
Concept	Zero-bias Schottky diode	
Terahertz bandwidth	50 - 1500 GHz	
Noise-equivalent power	7 pW/sqrt(Hz) @ 100 GHz 100 pW/sqrt(Hz) @ 1 THz	70 pW/sqrt(Hz) @ 100 GHz 1000 pW/sqrt(Hz) @ 1 THz
Responsivity	25000 V/W @ 100 GHz 2000 V/W @ 1 THz	250 V/W @ 100 GHz 20 V/W @ 1 THz
Amplifier bandwidth	10 Hz - 1 MHz	10 MHz - 4 GHz
Warranty	1 year	



Cw-terahertz spectrum of air with water vapour lines, recorded with a GaAs photomixer-emitter and a Schottky receiver.



Terahertz pulses at 80 MHz repetition rate, detected with a high-bandwidth Schottky receiver. The figure shows a reference trace in air, and pulses transmitted through polyamide (PA) and glass fiber composite (GFC) samples.

Further reading:

F. Rettich et al., *Field intensity detection of individual terahertz pulses at 80 MHz repetition rate;* J Infrared Milli. Terahz. Waves **36** (2015) 607-612.

Accessories
Optomechanics

Key Features

- Versatile optomechanics for transmission measurements
- 2 or 4 off-axis parabolic mirrors (collimated / focused beam)
- Compact reflection head, 3 mm spot size

#BG-001784, optomechanics with four mirrors.

#OE-000888, reflection head.

Three different sets of optomechanics, designed for the most common beam-path configurations, complement the list of terahertz accessories.

For transmission-mode experiments, two rail-based assemblies produce a collimated terahertz beam (2-mirror setup), or an additional focus (4-mirror setup), respectively. Both versions include precise 3-axis stages for the photomixers, mounting mechanics for the parabolic mirrors, and a manual translation stage. For applications that require a reflection geometry – for instance, layer thickness measurements on opaque substrates –, TOPTICA provides a dedicated reflection head. The compact, handheld module uses four mirrors to generate a focus at the location of the sample.

Specifications	#BG-001481 (2-mirror setup)	#BG-001784 (4-mirror setup)	#OE-000888 (Reflection head)
User mode	Transmission	Transmission	Reflection
No. of parabolic mirrors	2	4	4
Collimating mirrors	ø 2“, focal length 3“	ø 2“, focal length 3“	ø 1“, focal length 2“
Focussing mirrors	-	ø 2“, focal length 2”	ø 1“, focal length 4“
Focus size	-	Approx. 2 mm	Approx. 2.5 mm
2 xyz stages for photomixers	Included	Included	-
Manual delay stage	Included	Included	-
Motorized delay stage	No, please see Phase Modulation Extension		
Optical rails	Included	Included	-
Compatibility	TeraFlash, TeraScan 1550, TeraScan 780	TeraFlash, TeraScan 1550, TeraScan 780	TeraFlash, TeraScan 1550

Time-Domain vs. Frequency-Domain

Pick One: Pulsed or cw Terahertz?

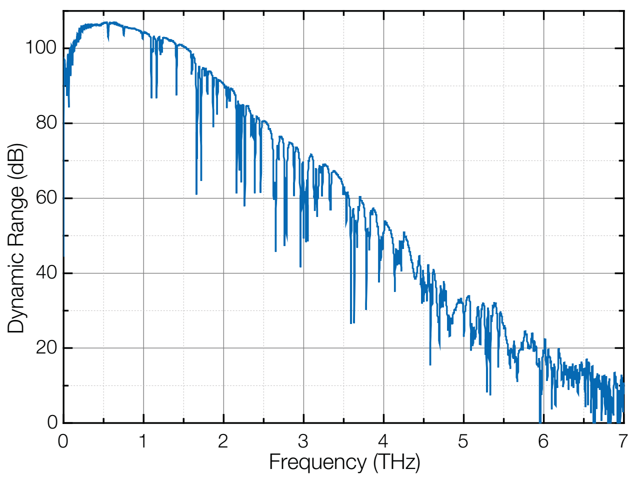
Highest bandwidth with time-domain systems

Time-domain and frequency-domain techniques each have merit. Time-domain spectroscopy offers the advantage of a very broad bandwidth; spectra acquired with photoconductive switches extend beyond 5 THz, and crystal emitters even achieve 10 THz. Measurement speed provides the second advantage. The TeraFlash acquires a single spectrum in less than 50 ms, and the collection of 1000 averages, which is an extremely efficient method to reduce the noise level, is completed in less than a minute. Time-domain systems also lend themselves to thickness measurements, e.g. of plastic components, or of paint and coating layers, where depth information is retrieved via time-of-flight measurements. The broad spectrum translates into micrometer-level thickness resolution.

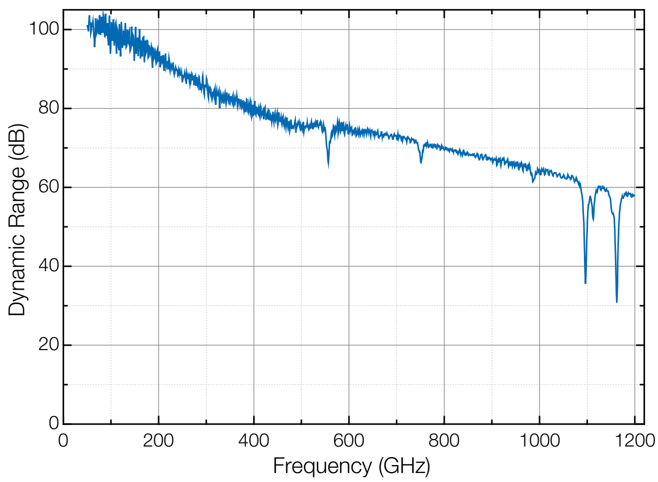
Best resolution with frequency-domain systems

Frequency-domain spectroscopy is the preferred choice for applications requiring highest spectral resolution. While a pulsed spectrometer offers a resolution on the 10 GHz level, cw systems allow frequency steps with single-megahertz precision. Gas sensing, specifically at low pressure, benefits from the precise frequency control of TOPTICA's TeraScan platforms.

In addition, cw-terahertz systems enable spectrally-selective measurements, making it possible to zoom in on one spectral signature (e.g., to measure the strength of a single absorption line in an industrial process line). In terms of system complexity, frequency-domain systems do not require a delay stage, therefore the price is lower than that of their pulsed counterparts.



TD-Terahertz: More than 6 THz bandwidth.



FD-Terahertz: Single-megahertz resolution.

Specifications	**Cw Terahertz Systems**	**Pulsed Terahertz Systems**
Bandwidth	0.05 – 2.7 THz, limited by lasers	0.1 – 5 .. 10 THz, depending on emitter
Peak dynamic range	> 90 dB	> 90 dB (95 dB typ.)
Frequency resolution	< 10 MHz	10 GHz typ.
Spectral selectivity	Yes	No
Acquisition time (spectrum)	Minutes to hours, depending on resolution and lock-in time	Milliseconds to minutes, depending on number of averages
Applications		
Plastic inspection	++	++
Paint and coating layers	0	++
Paper quality control	++	+
Hydration monitoring	++	++
Ultrafast dynamics	-	++
Gas sensing	++	0
Fundamental physics	++	++
Suitability: ++ Excellent	+ Good 0 Limited - Not suitable	

Order Information

Product Name	Order Information	Page
TeraFlash	Time-domain terahertz platform with FemtoFErb THz FD6.5, SM/PM fiber delivery, delay stages, InGaAs-based photoconductive switches, laptop + software	13
FemtoFiber pro IR	High-power ultrafast Erbium fiber laser, 1560 nm	14
FemtoFiber pro IRS	Erbium fiber laser with additional pulse compression (< 40 fs)	14
M40	Repetition rate 40 MHz @ identical average power (only for FemtoFiber pro IR and NIR)	14/15
FF VAR	Variable repetition rate (± 100 kHz relative to nominal rate)	14/15
FF LRC	Laser repetition rate control: Phase-locked-loop electronics for synchronization to an external reference signal	14/15
FemtoFiber pro NIR	Frequency-doubled ultrafast Erbium fiber laser, 1560 nm and 780 nm,	15
Two-color output	Simultaneous availability of the fundamental and frequency-doubled wavelength (2 output ports)	15
FemtoFErb 1560 THz	Compact, ultrafast fiber laser with “QuTE” soft-start mechanism, free-beam output	16
FemtoFErb THz FD6.5	Compact, ultrafast fiber laser with “QuTE” soft-start mechanism, SM/PM fiber delivery	16
FemtoFErb 780	Compact, frequency-doubled ultrafast fiber laser	16
FF Smart Switchbox	Switchbox and power supply for stand-alone operation of any FemtoFErb laser	16
#EK-000781	InGaAs-based photoconductive switch for terahertz generation	17
#EK-000782	InGaAs-based photoconductive switch for terahertz detection	17
TeraScan 780	cw-terahertz spectroscopy platform with two DFB lasers at 780 nm, DLC Smart controller, and two GaAs photomixers	19
TeraScan 1550	cw-terahertz spectroscopy platform with two DFB lasers at 1.5 µm, DLC Smart controller, and two InGaAs photomixers	19
TeraBeam 780	Two-color DFB laser at 780 nm, with DLC Smart controller, fiber-optic beam combination and software GUI	20
TeraBeam 1550	Two-color DFB laser at 1.5 µm, with DLC Smart controller, fiber-optic beam combination and software GUI	20
THz Tuning Ext. 2.0	3rd laser head for tuning range extension to 2.0 THz*	21
THz Tuning Ext. 2.7	3rd laser head for tuning range extension to 2.7 THz*	21
THz Phase Mod / NIR	Twin fiber stretcher for terahertz phase modulation, 780 nm**	22
THz Phase Mod / IR	Twin fiber stretcher for terahertz phase modulation, 1.5 µm**	22
#EK-000831	GaAs photomixer module for cw-terahertz generation at 780 nm	23
#EK-000832	GaAs photomixer module for cw-terahertz detection at 780 nm	23
#EK-000724	InGaAs/InP-based photodiode for cw-terahertz generation at 1.5 µm	23
#EK-000725	InGaAs/InP-based photomixer module for cw-terahertz detection at 1.5 µm	23
#BG-001481	Optics assembly for transmission measurements, incl. 2 parabolic mirrors (collimated beam)	25
#BG-001784	Optics assembly for transmission measurements, incl. 4 parabolic mirrors (collimated beam + additional focus)	25
#OE-000888	Reflection head, incl. 4 parabolic mirrors	25
*	Note: The Tuning Range Extension requires a TeraScan 1550 or TeraBeam 1550 system as base unit.	
**	Note: The Phase Modulation Extension requires a set of seed lasers. Please refer to the pages on the TeraScan / TeraBeam systems.	

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